Cafe Scheduling Optimization Simulation
Project Proposal
Repository: https://github.com/Baesiann/CS4632_Kenneth_Burke

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1. Project Overview

1.1. Domain

Service industry- specifically, coffee shop operations and staffing efficiency.

1.2. Problem Statement

This simulation addresses the question: *How should resources (staffing, skill allocation, and scheduling) be allocated to maximize profits in a cafe environment, while balancing customer satisfaction and staff utilization?*

1.3. Scope

The simulation will focus on customer arrivals, order processing, staff scheduling, and profit optimization. We will not simulate:

- Supply chain logistics (ingredient restocking, vendor relationships)
- Long-term customer loyalty trends outside of a single day
- External events, such as marketing campaigns, weather effects, or competition
- Costs of overhead outside of labor (i.e., rent, utilities)

Though we will be simulating

- Bursts of customer arrivals
- Menu complexity (different categories with varying service times)
- Customer abandonment
- Adaptive scheduling based on performance metrics

2. System Description

2.1. System Components

- **Customers:** Properties include arrival time, patience, and spending value. Behaviors include joining queues, waiting, or abandoning service.
- **Baristas:** Properties include service time (dependent on drink type), staffing cost, and skill level. Behaviors include serving orders, managing queues, and selectively taking complex/group orders based on skill.
- **Orders:** Properties include service duration and profit contribution. Behaviors include occupying barista capacity and generating revenue once completed.

2.2. System Dynamics

- Customers arrive over time, distributed according to probability models (single vs. group arrivals).
- Customers select queues, with higher-skilled baristas more likely to receive complex orders.
- Baristas serve customers sequentially, constrained by service times and skill.
- Customer abandonment occurs when wait times exceed patience thresholds.
- Profits are calculated as revenue minus staffing costs.

2.3. Core Models and Algorithms

1) **Probability Distributions:** Used to model customer arrivals and patience times (Doubly stochastic Poisson distribution to simulate customer arrivals, standard distribution to simulate patience).
2) **Queuing Models:** Each barista is represented as a single-server queue; group arrivals and barista skill add heterogeneity.
3) **Optimization:** Dynamic staffing schedule updated using historical metrics (profit, utilization, abandonment).

2.4. Assumptions

- Customers are independent and do not influence each other's patience.
- Barista performance is only influenced by skill level, not fatigue or learning.
- Prices are static and not affected by demand.

3. Implementation Approach

3.1. Programming Language

Python, due to its strong ecosystem for simulation libraries (`simpy`, `numpy`, `pandas`) and ease of statistical modeling.

3.2. Development Environment

- Jupyter Notebook / VS Code
- Libraries: `simpy` for discrete-event simulation, `matplotlib` for visualization, `pandas` for data handling.

3.3. Simulation Type

Discrete-event simulation, as customers and orders arrive in discrete time steps and events (arrival, service, abandonment) occur asynchronously.

3.4. Data Collection Plan

The following metrics will be recorded:

- Average customer wait time
- Customer abandonment rate
- Staff utilization (busy vs. idle time)
- Total profit (revenue - labor costs)

4. Literature Review

4.1. Core Models and Algorithms

- Queuing theory in service systems
- Poisson arrival processes in retail
- Optimization in workforce scheduling
- Simulation modeling of service industries
- Studies on skill-based service allocation

For each source:

1) Describe the model/algorithm
2) Explain its relevance to the cafe simulation
3) Note what aspects will be adapted

4.1.1. Bayesian inference for queuing networks and modeling of internet services. Sutton and Jordan [1] explore domains that work with parallel servers and queuing networks, closely simulated what I am trying to achieve for my project. As customers will be routed from a main queue into separate barista queues, Sutton develops methods to analyze queuing networks. As the scheduling manager will be working without information about customer distribution, it would have to extrapolate its own inferences from collected data, a topic that is tackled using Bayesian inference. Since Bayesian inference and MCMC seem overkill for what I am trying to achieve, I will take ideas about updating data over time and apply a simpler algorithm, such as a moving average.

4.1.2. Simulation-Optimization of a Coffee Shop in Business District. The domain of this article [2] closely simulates the domain of my project. Similar aspects that I will include in my own project relate to a café with customer arrivals, staffing optimization, and variable volumes pertaining to the time of day. This source will prove to be a foundational comparative model to my own data and customer generation model. Many aspects of my own project will be different in the sense of analysis on a lower level, as in staff skill and order complexity, not to mention that instead of the comparison of static schedules, I will be implementing a dynamic schedule that the schedule manager changes as they see fit by prediction models.

4.1.3. Modeling and forecasting call center arrivals. This article [3] reviews the Poisson arrival process and compares it to a doubly stochastic Poisson process, where the doubly stochastic Poisson process would make my customer arrivals more realistic, as customers tend to show up in random bursts rather than steady random ones. Many queuing simulations use a Poisson distribution to simulate customer arrivals, but considering the arrival rate itself to be a stochastic process adds another layer of realism to my project. In addition, they use different windows to calculate different predictions, depending on the amount of information available. This pertains to my project as the only data that will be acquired is from the simulation itself; being able to utilize different algorithms on different available data. (Single day vs. Several days) would be beneficial to my scheduling manager.

4.1.4. Modeling Queuing System in Retail using Discrete Event Simulation. This paper [4] covers a build of a discrete-event simulation model to study queues and employee scheduling, closely related to the domain of the project. They explore different improvement strategies, from service appointments to workstation differences. What is different that I did not initially consider was the variable service time, where the low demand hours provide slower service than the high demand hours do. I will take note on what they use for key performance indicators, such as waiting time, staff utilization, and queue lengths. Their use of historical data also closely simulates what I am attempting to accomplish in my own project.

4.1.5. Simulation and Analysis of Queueing System. This thesis [5] builds a discrete-event simulation framework, implementing both single-server and multi-server queuing models. The use of historical data to parameterize the system is also evident through the use of real historical data to infer arrival. This source provides a good framework for my multi-server goals, as well as providing clear architecture that will assist in my own design of entities, metrics, events, and the interpretation of collected data. As opposed to the uniform multiserver models, my 'servers' will be operating at different capacities in accordance to their skill. Though, the data pre-processing models such as the data clean algorithm could prove to be useful.

References

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[5] Y. Zhang, "Simulation and analysis of queueing system," Master's Thesis, KTH Royal Institute of Technology, 2019. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1421234/FULLTEXT01.pdf